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IRRADIATION FACILITIES AT THE ADVANCED TEST REACTOR

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Introduction

The Advanced Test Reactor (ATR) is the third generation and largest test reactor built in the Reactor Technology Complex (RTC – formerly known as the Test Reactor Area), located at the Idaho National Laboratory (INL), to study the effects of intense neutron and gamma radiation on reactor materials and fuels. The RTC was established in the early 1950s with the development of the Materials Testing Reactor (MTR), which operated until 1970. The second major reactor was the Engineering Test Reactor (ETR), which operated from 1957 to 1981, and finally the ATR, which began operation in 1967 and will continue operation well into the future. These reactors have produced a significant portion of the world's data on materials response to reactor environments. The wide range of experiment facilities in the ATR and the unique ability to vary the neutron flux in different areas of the core allow numerous experiment conditions to co-exist during the same reactor operating cycle. Simple experiments may involve a non-instrumented capsule containing test specimens with no real-time monitoring or control capabilities[1]. More sophisticated testing facilities include inert gas temperature control systems and pressurized water loops that have continuous chemistry, pressure, temperature, and flow control as well as numerous test specimen monitoring capabilities. There are also apparatus that allow for the simulation of reactor transients on test specimens.

ATR Description and Capabilities

The ATR is considered to be among the most technologically advanced nuclear test reactors in the world. Though the reactor is used primarily by the United States Department of Energy's (DOE) Naval Nuclear Propulsion Program, since the early 1990s, about one-third of the ATR's test space has been made available for other research programs. The ATR is now serving other government programs, as well as commercial and international research programs on projects from isotope production to irradiations for existing reactor plant life extension and development of the Generation IV reactors. The ATR has a maximum thermal power of 250MW, and can provide maximum neutron fluxes of 1E15 thermal and 5E14 fast (E> 1 MeV) neutrons per square centimeter per second. These very high flux rates can accelerate the neutron fluence to materials and fuels up to a factor of ten over what would be seen in a typical power reactor. The unique capability of the ATR to provide either constant or variable neutron flux during a reactor operating cycle makes irradiations in this reactor very desirable. In addition, the ATR provides researchers with many other capabilities including large test volumes, a variety of fast to thermal flux ratios, a constant axial (vertical) flux profile shape, power tilt capability, individual experiment control, high reactor availability, and frequent experiment changes (approximately every seven weeks). These capabilities coupled with the numerous (seventy-seven) test positions available and various support facilities (including experiment assembly and Post Irradiation Examination facilities) make the ATR a very versatile and desirable irradiation facility.

The simplest experiment performed in the ATR is a static capsule experiment. The material to be irradiated is housed (either sealed or unsealed depending on the specific experiment) in aluminum, zircaloy, or stainless steel. The experiment is then typically placed in a holder that locates it in the chosen test position in the ATR. These types of experiments have no active instrumentation, but can include passive instrumentation such as flux-monitor wires or temperature melt wires for examination following the irradiation. The next level in experiment complexity is an actively controlled capsule. During an experiment using active temperature control (most commonly sought controlled parameter), conducting (helium) and insulating (typically neon or possibly argon) gases are mixed to control the thermal conductance across a predetermined gas jacket. Thermocouples measure temperature continuously and provide feedback to the gas system that adjusts the mixture to achieve the desired temperature. The pressurized water loop experiment is the most comprehensive type of testing performed. An in-pile tube runs through the reactor core from vessel top to bottom and is attached to its own individual pressurized water coolant system. The cooling system includes pumps, valves, electrical heaters, heat exchangers, ion exchangers and a pressurizer to control the experiment flow rate, temperature, chemistry and pressure. Loop tests can precisely represent conditions in a commercial pressurized water power reactor, and can include transient testing using one of ATR's two Powered Axial Locator Mechanisms (PALM). The PALM tests usually last from a few hours to a few days, and are described in more detail later. Some other experiments may be removed from the reactor during a PALM test due to the changing reactor conditions. Hence, this is perhaps the most costly type of test to perform in the ATR. Each of these types of experiments is described in detail later.

Cranes and special handling tools are available to either remove or insert customer hardware into the reactor. Underwater storage facilities and working trays (for experiment assembly/disassembly) are available in the large ATR canal adjacent to the reactor vessel. Facilities and specialized counting equipment are available at the Reactor Technology Complex to analyze flux wires from experiment irradiations and calculate total neutron fluence or neutron spectra data. Based on the complexity of the experimental needs of the customer, ATR operations can also provide real time monitoring and data collection equipment.

ATR Operations, Quality and Safety Requirements

Operation of the Advanced Test Reactor is based on a yearly schedule divided into multiple time intervals called "cycles". The length of a reactor cycle (specified in days) and the reactor power (specified in Megawatts) is variable, and dependent upon the customer's experimental requirements and the design basis reactor safety documentation[2]. In order to maintain reactor operational efficiency, equivalent reactor availability, and meet the needs of the customers, the reactor schedule is prepared a year in advance. Integrated into this schedule are planned reactor outages for routine reactor/plant maintenance and removal/insertion of customer experiments.

All experiments to be irradiated in the ATR are controlled by an American Society of Mechanical Engineers (ASME) NQA-1 quality assurance program with multiple reviews/approvals prior to acceptance of customer hardware for irradiation. In addition, for every ATR cycle, complex multi-group neutron diffusion and transport theory calculations are performed, reviewed, and approved for both fuel and experiments to verify the reactor will operate within the required safety parameters to protect the public and environment. Experiment operational parameters (flow, temperature, pressure, and heat generation) and experiment failure modes are compared to the ATR design basis safety documentation to complete the necessary reviews to ensure safe operation of the ATR and the experiment.

Static Capsule Experiments

Static capsules (commonly referred to as drop-in capsules) may include special passive instrumentation for monitoring specific parameters (i.e. melt wires for temperature, flux wires for neutron fluence, etc.) during irradiation (Fig. 1). The temperature of a static capsule may also be controlled, within limits, by incorporating a small insulating gas jacket (filled with an inert gas) between the specimens and the outside capsule pressure boundary. The width of the gas jacket, the type of gas, and the gamma and reaction heating characteristics of the specimens and capsule materials are used to provide the irradiation temperature desired by the experimenter. Static capsules may vary in length (from a few centimeters to 1.2 meters) and diameter (from 1.2-cm to 12.7-cm), and are usually sealed in aluminum, zircaloy, or stainless steel tubing to provide containment. Depending upon the contents and pressure of the capsule, a secondary containment may be included to meet the ATR safety requirements. Static capsules, which are usually contained in a basket, are uniquely designed for each customer's needs. This type of experimentation is usually less expensive and requires less lead time to insert an experiment into the ATR than any of the other types of experiments due to their simplicity. However, this type of experiment also has less flexibility and control of operating parameters during the irradiation. In addition, the passive instrumentation (if included) can only be removed during reactor outages and examined later to determine the conditions that occurred during the experiment irradiation.

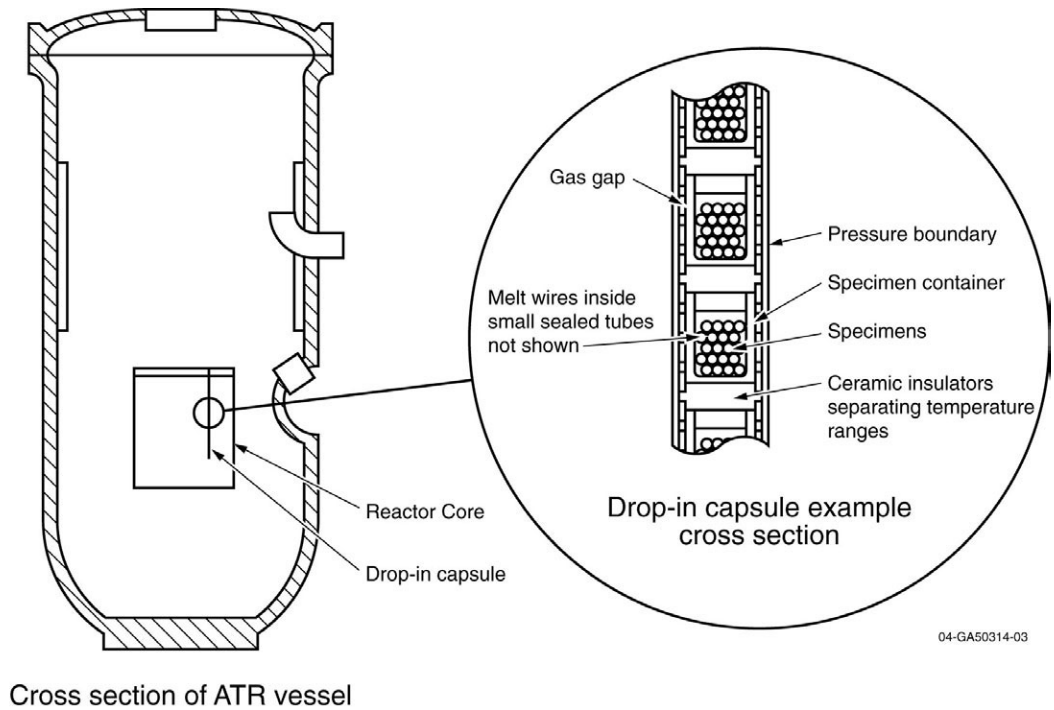

Figure 1. Static (or Drop-in) Type Capsule Experiment

Lead Experiments
The next level of testing in order of complexity provides continuous monitoring (and possibly control) of experiment parameters during irradiation utilizing instrumented leads in the capsules. These experiments are commonly called 'lead experiments' (figure 2) after the instrument leads they contain. The experiment containment is very similar to a static capsule, with the major difference being an umbilical tube attached to the top of the containment. The umbilical tube is used to house the instrumentation and control leads (thermocouples, pressure taps, neutron detectors, gas lines, etc.) from the experiment position in the core to the reactor vessel wall penetration where they can then be connected to the data collection/monitoring and control equipment. Each instrumented lead experiment, which may contain several vertically stacked capsules, and its associated umbilical tube routing is uniquely designed for the specific irradiation experiment within the ATR.

The most common parameter to be monitored and controlled during irradiation is the specimen temperature. Over several decades, individual programs (notably the New Production Reactor program) have designed, built, and irradiated instrumented lead experiments in the ATR with temperature control. The temperature of each experiment capsule is controlled by varying the thermal conductivity of a purge gas mixture in a very small gas jacket between the specimens and the experiment containment. This is accomplished by blending two gases with dissimilar thermal conductivities. Helium and neon have been chosen to provide the thermal conductivity variability, but other gases may be used if desired. Normal operations call for the gases to be blended automatically to control the specimen capsule temperature. The gas blending capability permits a blend range of 98% of one gas to 2% of the other allowing a very broad range of control. A completely separate gas supply system using similar equipment has also been installed to maintain a controlled atmosphere cover gas (e.g. oxidizing, etc.) within a lead experiment capsule(s) during irradiation.

Temperature measurements are taken with at least two thermocouples per experiment capsule. The thermocouples typically used are type K (special grade, +/- 0.4%) with 1.6-mm sheath diameter and high purity magnesia insulation. Other arrangements are possible including multi-junction thermocouples within a single sheath. The type K calibration was selected and is used in pairs to assure long term service in the high radiation environment. The thermocouple reading is used as the direct control parameter to the gas mixing functions. Additionally, the control systems provide automatic gas verification to assure the correct gases are connected to supply ports in the system to prevent any inadvertent temperature excursions.

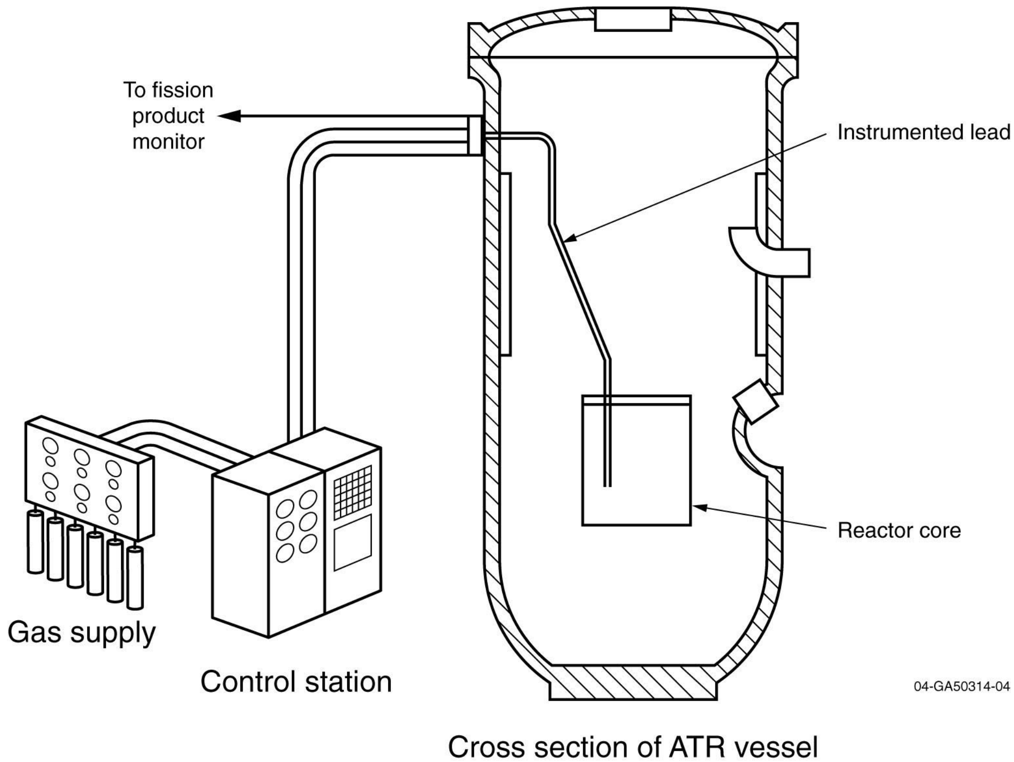

Figure 2. Lead Experiment Assembly

Monitoring of the exhaust purge gas is possible and there are several systems available for consideration that have been employed on previous temperature controlled experiments conducted in the ATR. Alarm functions are provided to call attention to circumstances such as temperature excursions or valve position issues. Helium purges to individual specimen capsules are under automatic control in the unlikely event that the availability to measure or control capsule temperature is lost. In order to assure the time response is minimized; the gas system provides a continuous flow to the specimen capsule. Manual control capability is provided at the gas blending panels to provide helium purge in the event of a computer failure. Data archive and acquisition are also included as part of the control system function. Real time displays of all temperatures, all gas mixtures, and all alarm conditions are provided in the operator control station and at the experimenter's monitor located in the reactor building. All data is archived to removable media. The data is time stamped and recorded once every ten minutes or more frequently by exception not to exceed a rate of once every ten seconds. The control processor will record these values in a circular first-in, first-out format for at least six months.

The benefits of performing an instrumented lead experiment are more precise monitoring and control of the experiment parameters during irradiation as well as monitoring the temperature control exhaust gas to establish specimen performance during the irradiation. However, since lead experiments are much more complex and require more operator involvement during irradiation, they have the detriments of higher total experiment costs and a longer lead time to get an experiment into the reactor than a static capsule. There are also higher costs and risks associated with removal and re-installation of an instrumented lead experiment in the reactor for specimen replacements or to avoid a short high power ATR operating cycle.

Irradiation Test Vehicle

In 1999, the Irradiation Test Vehicle (ITV) was installed in ATR's center flux trap. The ITV utilized the same instrument leads, temperature control technique and exhaust gas monitors as the lead experiments previously described. In fact, the ITV is really a special type or sub-set of the standard lead experiments. The ITV facility provided a pressure boundary, gas jacket, and temperature control gas for an experiment assembly as well as the umbilical tube needed for the instrument leads or environmental (either gas or water) system for the experiment. By using this facility, the experimenter could avoid the cost of design and fabrication of the experiment pressure boundary and the umbilical tube required to house the instrument leads and temperature control gas lines to experiment. Since this facility was located in the center flux trap (at the very center of the ATR core), the ITV provided new opportunities to perform temperature controlled material irradiations in high flux regions at reasonable cost to users. The ITV was removed from the ATR during the last core replacement in January 2005, but could be re-installed for an irradiation program when the need arises.

Development of the ITV called upon the broad experience gained from previously instrumented experiments including design, analytical modeling, blended gas temperature control and automated computer control systems. The ITV can provide up to 650 cc of instrumented irradiation volume in 15 capsule positions, each capable of being controlled at +/- 5 C of its selected temperature. The largest specimen that could be irradiated in the ITV is approximately 22-mm diameter. Depending on the vertical position in the core, the temperature of each specimen capsule may be controlled up to 800 °C or possibly higher depending on the internal heating and heat transfer properties of the materials used in the experiment. This facility can provide a test platform that permits experimenters to subject a broad range of material specimens to varying ranges of temperatures and neutronic conditions. The ITV facility also permits changing of specimens with as little imposition on reactor operations as possible. Experiment handling takes place within the standard seven-day outage between the normal forty to fifty day operating cycles.

The ITV consists of three concentric tubes (called mini-in-pile tubes or MIPTs) to meet pressure boundary, gas line and thermocouple distribution as well as experiment location requirements. The ITV in-core arrangement (without the experiment assembly) consists of the pressure tube and the gas channel tube. The pressure tube provides the pressure boundary between the reactor coolant and the specimen holders. The gas channel tube (located within the pressure tube) is machined to incorporate axial channels in its external surface to route gas to each experiment chamber. The gas channel tube was installed into the pressure tube with an interference shrink fit to assure a seal between each gas channel, and has seventeen channels that terminate at elevations corresponding to the individual gas chamber positions. Five channels are for supply and ten for exhaust (the other two channels are for MIPT sweep gas supply and exhaust). Although five separate temperature control chambers (or zones) are provided in each MIPT, the experimenter may select to use fewer than five capsules simply by having the experiment designed with a longer experiment capsule and locating the seal ring spacers between capsules at different elevations.

Spectral tailoring is accomplished by using neutron filtering materials, such as boron, that will affect the flux to which the experiment specimen is exposed. These filtering materials can be included as part of the experiment assembly inside the MIPT or they can be located in a channel outside of the MIPT in an aluminum filler especially provided for this purpose. The outside filler material is replaceable during reactor outages. By incorporating the neutron filter in the outside filler, filtering capability can be retained for long durations by replacing filters as their neutron poison depletes. The use of neutron filtering material must be carefully analyzed to limit its impact on reactor operating cycle length and power level.

As indicated earlier, temperature measurement and control is accomplished in the same manner as the lead experiments discussed in the previous section. The control gas system provides individual supply lines to the supply channels of the gas channel tube from the gas-blending panel. The blended gas flows through the individual experiment chambers and out the exhaust channels to the exhaust gas manifold located in a room directly below the reactor tank. All gas connections to the ITV are made through the reactor bottom head.

The exhaust gas can be monitored by the same systems as the standard lead experiments discussed in the previous section before being discharged to the main reactor building ventilation exhaust.

The ITV control system uses fiber optic links and an Ethernet data bus for the communication needed to access the thermocouple outputs and to manipulate the control gas system components. This assures the appropriate gas blends are sent to the corresponding experiment specimen sets. The automated Distributed Control System (DCS) is designed to monitor, control, archive data, and generate reports without the attention of operators during reactor operations. Abnormal conditions are alarmed and procedures identify the appropriate operator response. Monitoring and archiving of specimen temperature control gas mixture, and alarm status is provided. The system provides normal onsite experiment monitoring and can provide offsite real-time data. Data archival, reporting format and frequency can be directed by the test sponsor.

The initial fabrication and installation of the ITV systems addressed the major complexities that often are the greatest threat to successful experiment programs. All ITV systems were to remain intact when experiment test trains are removed. New test trains simply established the control parameters, analytical determined the gas jacket dimensions, and were then assembled and inserted in the ITV.

The benefits of performing an ITV experiment are identical to those of a standard lead experiment, plus the added advantage of the reduced costs of design and fabrication identified earlier. An ITV experiment also has the detriments of a standard instrumented lead experiment of higher total experiment costs and a longer lead time to get an experiment into the reactor than a static capsule. However, the costs and risks associated with removal and re-installation of an ITV experiment in the reactor to avoid a short high power ATR operating cycle are less than a standard instrumented lead experiment because of the ability of ITV experiments to utilize the center flux trap top head penetration.

In-Pile Loop Experiments

When viewed from above, the ATR fuel in the reactor core resembles a four-leaf clover created by the serpentine fuel arrangement. The fuel arrangement creates nine primary test locations called flux traps. Five of the flux traps contain In-Pile Tubes (IPT). The other four positions can contain static capsules, lead experiments, or other experiment facilities such as the ITV as mentioned above. An IPT is the in-vessel reactor component of a pressurized water loop and creates a unique testing facility. Each IPT is connected to a separate pressurized water loop, which allows material testing at different pressures, temperatures, flow rates, and water chemistry (Fig. 3). The IPT provides a barrier between the reactor water and the pressurized loop coolant for the experiment, similar to the arrangement of a MIPT described in the ITV section above. Although isolating the experiment from the reactor water, it still subjects the test materials to the neutron and gamma environment of the reactor. The IPT extends completely through the reactor vessel with closure plugs and seals at the reactor's top and bottom heads. This allows the top seals to be opened and each experiment to be independently inserted or removed. The experiments are suspended from the top closure plugs using hanger rods. The hanger rods position the test within the neutron flux and provide channels for test instrumentation. Anything from reactor fuel rod bundles to core components can be irradiated or tested.

The experiment designers, though constrained by ATR's unique operating and safety requirements, are free to develop a test with specific operating conditions within the space and operating envelope created by the IPT and loop. A loop experiment can contain a variety of instrumentation including flow, temperature, pressure, differential pressure, fluence, fission product monitoring, and water chemistry. All of these parameters can be monitored and controlled by the Loop Operating Control System (LOCS) or by operator intervention. The LOCS is a state-of-the-art computer system designed specifically for the ATR loops. The system monitors and controls all aspects of the loop operations (flow, pressure, and temperature) for all five loops simultaneously and also provides emergency functions and alarms for each loop. This information is displayed on the Loop Operating Console and interfaces with the reactor control system, which is a similar system controlling the reactor. Loop Operators are stationed at the controls to operate and monitor the systems to meet the test sponsor requirements. All test specific information being monitored, including reactor power levels, can be averaged daily, hourly or every 2 to 3 seconds. However, the massive amount of information is typically averaged over longer periods before being permanently recorded and transferred to the sponsors. If desired, any off-normal event can be recorded on a shorter time period and the data provided.

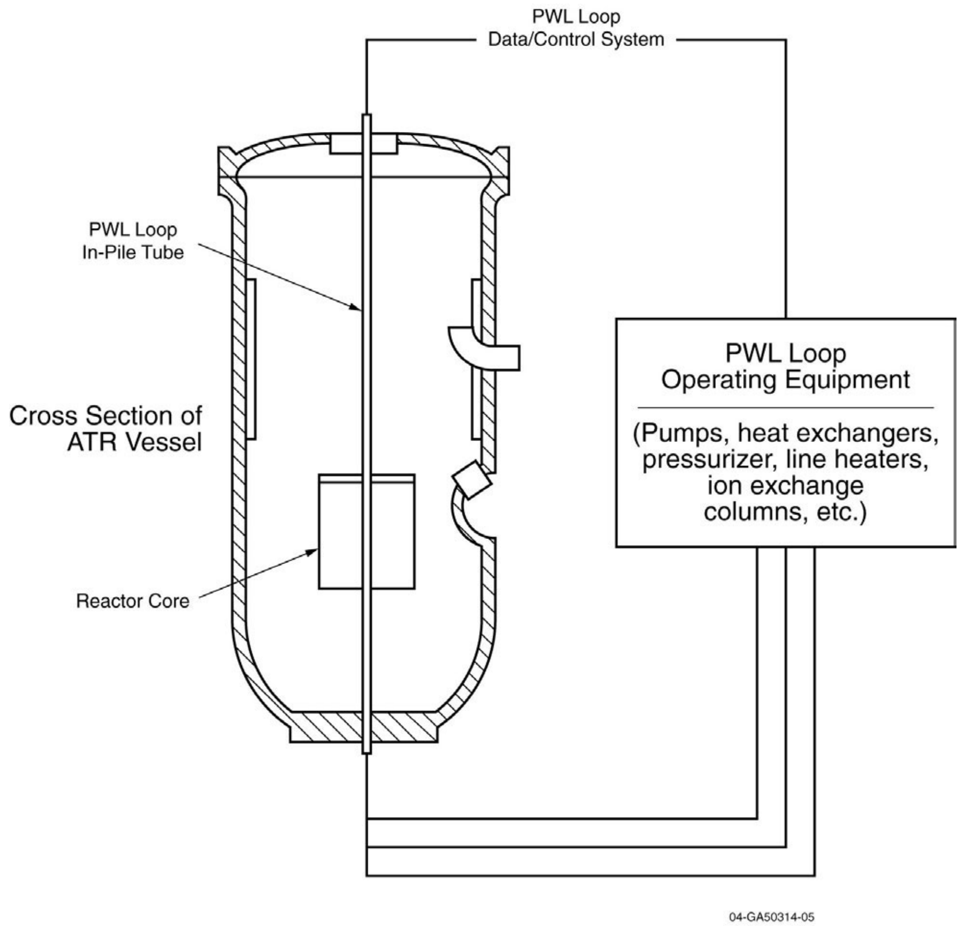

Figure 3. Pressurized Water Loop in the ATR

Test parameters are measured using a variety of instrumentation. Digital outputs for all the measurement devices are routed to the LOCS. Flow is measured in-core and out-of-core using flow venturis and/or orifice plates. Pressure, differential pressures and level indications are measured throughout the loop system with impulse lines at various locations including pump inlets and outlets, IPT inlet and outlet, test inlet and outlet, pressurizer surge line, etc. Standard pressure gauges are also installed in the secondary cubicles with impulse lines connected to the loop. Temperatures are measured with a variety of thermocouples installed either directly in the test specimens or merely in the loop coolant. Loop thermocouples are typically installed in thermowells welded into the loop piping, which allows thermocouple replacement without opening the loop system. Fission product inventories in the loop water are measured by gamma detectors in the loop cubicles, and are also measured by taking water samples. Loop chemistry is monitored with on-line instrumentation, and again water samples are taken and analyzed in the ATR Lab. The chemistry is maintained with on-line purification systems and adjusted with a chemical addition system.

Fluence is typically calculated based on actual operating powers obtained from the reactor control system. Actual fluence can be confirmed by measuring flux wires installed in or around the test. Since the flux wires must be removed from the test and counted, they are passive devices used to confirm predicted values. On-line fluence measurements can be obtained, though not typically done, by installing a Self-Powered Neutron Detector in the test section.

Loop experiments are loaded into the IPT either from the ATR canal using the ATR Transfer Cask or directly from the shipping casks. These are 30-ton shielded casks specifically designed to interface with the ATR reactor top. The loop is depressurized and partially drained, the IPT closure seals are removed, and the cask is set over the IPT and the test lowered down into the IPT. The cask is then removed, the closure seals are reinstalled, the instrumentation lines are connected and the loop refilled.

There are two Powered Axial Locator Mechanism (PALM) drive units that can be connected to specially configured tests in the loop facilities so that complex transient testing can be performed. The PALM drive units move a small test section from above the reactor core region into the core region and back out again either very quickly, approximately 2 seconds, or slowly depending on test requirements. This process simulates multiple startup and shutdown cycles of test fuels and materials. Thousands of cycles can be simulated during a normal ATR operating cycle. The PALM drive units are also used to precisely position a test within the neutron flux of the reactor and change this position slightly as the reactor fuel burns.

The benefits of performing a pressurized water loop experiment are (as with the instrumented lead experiments) more precise monitoring and control of the experiment parameters during irradiation as well as monitoring the loop water chemistry to establish specimen performance during the irradiation. However, this type of experiment has the detriments of the highest total experiment costs and the longest lead time to get an experiment into the reactor.

Gas Test Loop

A proposed Gas Test Loop (GTL) for ATR is in its conceptual design phase, and therefore the features are still being identified and developed. The system is currently being planned for installation in one of the large flux trap positions in ATR to maximize the flux rates and experiment size available to experimenters. In addition to use of a flux trap position, currently consideration is being given to boosting the fast flux rate by including additional fuel around the outside of the test positions. Several different configurations have been proposed for the additional fuel and all are being evaluated for cost, manufacturability, and increased capabilities.

The current gas testing facilities at ATR utilize either stagnant or very low control gas flows (50 cc/min) and therefore rely on conduction and/or radiation heat transfer mechanisms. However, the GTL is envisioned to utilize convection heat transfer for cooling of the irradiation positions, which would greatly expand the capability of the ATR for testing gas reactor fuels. Helium is the bulk coolant under consideration and the heat rejection capacity of the gas system is still under development.

The current concept includes three irradiation mini in-pile tubes similar to the ones used in the ITV but slightly larger in diameter. In addition, there will be the capability to include several vertical positions in each in-pile tube similar to the ITV configuration. The individual experiment capsules will use helium/neon mixtures (or other inert gases) to provide fine temperature control for the experiment specimens within the in-pile tubes while the helium bulk coolant on the outside of the in-pile tube will provide the main heat rejection. The Gas Test Loop is anticipated to replace the ITV and have significantly increased capabilities. These features are currently being developed and will most likely be carried forward into the preliminary design phase of the project.

Interest in using the new GTL has been expressed by several countries involved in the Gen IV program, including Japan and France. This new capability at ATR for gas testing in conjunction with a higher fast neutron flux will be a definite boost to available testing options for the Gen IV community.

Future Testing

U.S. Department of Energy base programs at ATR are expected to continue well into future decades. Other federal, commercial and international programs will likely continue to utilize part of ATR as well. In anticipation of this, the INL will continue to develop facilities at ATR and make testing at ATR more user-friendly. The Irradiation Test Vehicle was the first such facility and provided rapid access at low cost to a temperature controlled facility in a high neutron flux. The Gas Test Loop is the next example of a facility being developed to enhance future testing in the ATR. Experiments are currently being conducted and other experiments are being planned for the future to support development of the Generation IV reactors. More collaboration with universities is being encouraged and an experiment/isotope shuttle facility may be added at a future date.

Support Facilities at RTC

RTC has the necessary facilities to support different testing programs. These facilities include modern fabrication facilities and a new Test Train Assembly Facility (TTAF). The fabrication facilities consist of dedicated weld and machine shops that contain computer-controlled fabrication equipment. The new TTAF is currently being brought into operation with a completely refurbished facility, specifically set up for test train assembly, and new updated equipment. The assembly capabilities include induction brazing, electro-plating, thermocouple potting and splicing, all types of welding including resistance spot welding (instrument leads) and autogenous welding, liquid nitrogen shrink fits, and a vacuum drying oven for removing moisture from porous materials (e.g. graphite, etc.). These facilities are staffed with personnel experienced in the delicate operations need to fabricate test trains such as machining of very small intricate parts, conducting induction brazing multiple thermocouples into a small diameter bulkhead, and performing welding inside of inert glove boxes on small intricate parts.

Conclusions

The ATR has a long history in fuel and material irradiations, and will be fulfilling a critical role in the future fuel and material testing necessary to develop the next generation reactor systems and advanced fuel cycles. The capabilities and experience at the ATR, as well as the other test reactors throughout the world, will be vitally important for the development of these new systems to provide the world with clean safe energy supplies in the future.

Acknowledgments

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